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Determination of optimum switching angles for speed control of switched reluctance motor drive system

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Turn-on angle and turn-off angle are the two switching angles that play a major role in deciding whether a switched reluctance motor (SRM) develops positive or negative, high or low electromagnetic torque. Switching angles are function of speed and change with acceleration, but this requires sophisticated and complex digital controllers for real time variation of switching angles as a function of rotor speed. This paper presents a methodology on the determination of fixed turn-on and turn-off angles that are optimum and provide satisfactory performance of the SRM drive during full-load operation. Experimental magnetization and static torque data are used for realistic simulation of dynamic response of a 4 kW, 4-phase, 8-pole stator, and 6-pole rotor configuration SR motor. The simulated performance of SRM drive system is presented to analyze the effect of different switching angles on full-load (25 Nm) starting performance of the drive in terms of speed, current and torque response. An optimum pair of turn-on and turn-off angle that ensures stable and satisfactory full-load operation is recommended.

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Switched reluctance motor (SRM) for variable speed application is a robust, reliable and almost maintenance free electric drive suitable for industrial, transport and domestic sector[1]. The specific advantages of SRM have made it a worthy competitor to converter/inverter fed AC/DC drives.

The high level performance expected from a variable speed drive includes minimum torque ripple, low steady state error, reduced speed overshoot, low starting time and reduced speed oscillation. Such a performance is not easy to meet, as it is required to accommodate a large number of system non-linearities. The electromagnetic torque developed by the SRM is a nonlinear function of stator current and rotor position θ. For forward motoring, the appropriate stator phase winding must remain excited only during the period when rate of change of phase inductance is positive. Else, the motor would develop braking torque or no torque at all. The value of inductance of a stator phase is maximum when its pole is directly opposite the rotor pole and is minimum when the inter-polar rotor region is opposite to it. Ideally, the stator phase must be energized when its inductance starts rising and must be de-energized when the phase inductance ceases to increase. The switching function, thus, must ensure that the current in phase winding reaches its reference value at the desired instant of inductance rise and is again brought to zero when inductance reaches its maximum and does not increase any further. However, due to delay in current rise and fall on account of winding inductance, the switch must be closed at a turn-on angle (also called advance angle) θ_{on} and must similarly be opened at a turn-off angle θ_{off}. These switching angles are variable and depend mainly on speed, and torque that depends upon the current in phase windings of SRM[2]. Here, the dc link voltage is assumed to be constant.

Various researchers[3-7] have elaborated on the performance of SRM with angle control. Orthmann and Schoner[3] have discussed the on-line calculation of turn-off angle for optimum torque output of SRM. Fixed switch-on and switch-off angle control scheme with flat-topped current has also been reported by Jin-Woo *et al.*[4], which emphasizes on the development of a proper voltage excitation scheme to form the required flat-topped current. Torque ripple reduction by turn-off angle compensation[5], reduction of SRM vibrations by random variation of control angles[6] and self-tuning of switching angle for speed control of SRM[7] have also been reported. However, it is observed from the available literature that any investigation on a single pair of turn-on and turn-off angle that provides satisfactory operation of SRM over a wide range of operating conditions has not been reported.

The motivation for the present work is to determine a typical pair of the switching angles on the basis of a comprehensive study of the performance of SRM with different fixed switching angles. In order to achieve this target, initially, no speed controller is used and a constant reference current is used to study full-load starting speed response of the SRM drive. This process eliminates the effect of controller gains on drive performance. Those switching angle pairs that give good results are then used with speed controller to analyze full-load starting performance. The pair that gives the best result is then selected as the optimum pair of fixed turn-on and turn-off switching angle.

The drive performance is evaluated in terms of highest average torque per ampere offering smooth starting under full load operation. Rotor speed, winding current and electromagnetic torque are also presented. Simulated results pertaining to starting time, overshoot, steady state error, settling time, full-load speed ripple and full-load torque ripple describe the effect of switching angles on drive operation. Comparative study[8] of PID (Proportional, Integral and Differential), sliding mode and fuzzy logic control for four-quadrant operation of SRM has suggested that the PID controller offers a simple control structure to achieve an optimum performance. Hence, in this study, PID controller has been used in speed loop for predicting the drive performance.

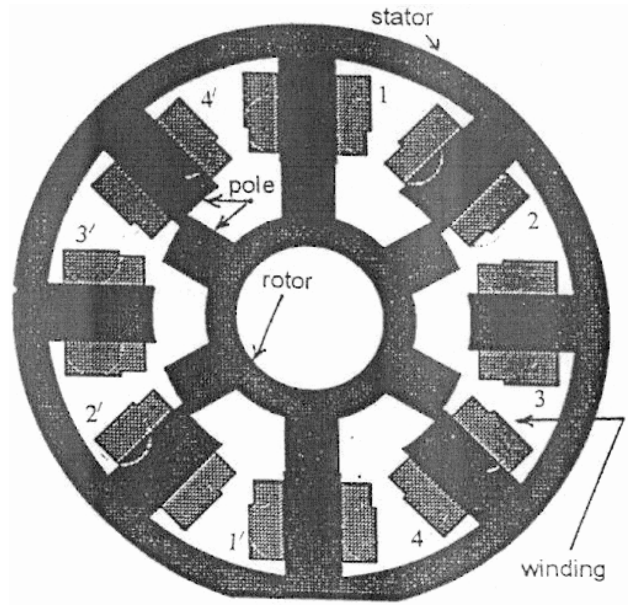


Fig. 1a — Cross-section of 4-phase SRM

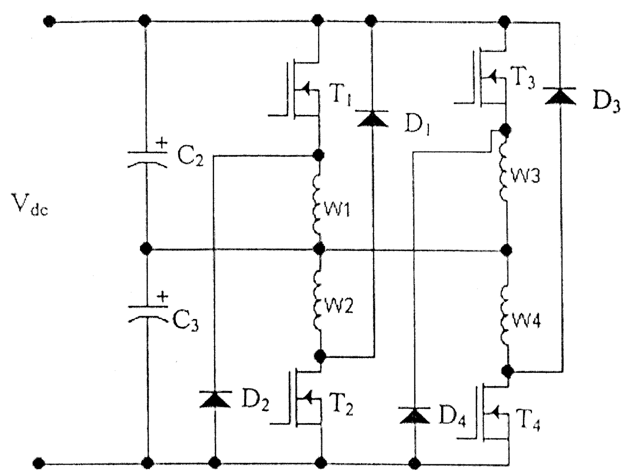


Fig. 1b — Mid-point inverter for SRM

Theoretical

Inductance profile and switching angles

The cross-section of 8/6 pole configuration SRM for which analysis has been conducted in this paper is shown in Fig. 1a. It is a four-phase machine excited by a semiconductor-controlled mid-point inverter as shown in Fig. 1b. This inverter has only one switching device per phase, which reduces control complexity and cost.

Ideal inductance profile of the four phase windings of motor versus rotor position θ is shown in Fig. 2a. The different zones of inductance, namely minimum inductance zone, rising inductance zone, maximum inductance zone and falling inductance zone of one phase of SRM are shown in Fig. 2b. The inductance profile of a switched reluctance motor depends upon its configuration and pole geometry and therefore the profile of say a 6/4 pole configuration SRM will be different from that of an 8/6 pole configuration motor. In the present case, the motor is an 8/6 pole configuration SRM with 20° stator pole breadth, 24° rotor pole breadth, 45° stator pole pitch and 60° rotor pole pitch. This results in 16° minimum inductance zone, 20° rising inductance zone, 4° maximum inductance

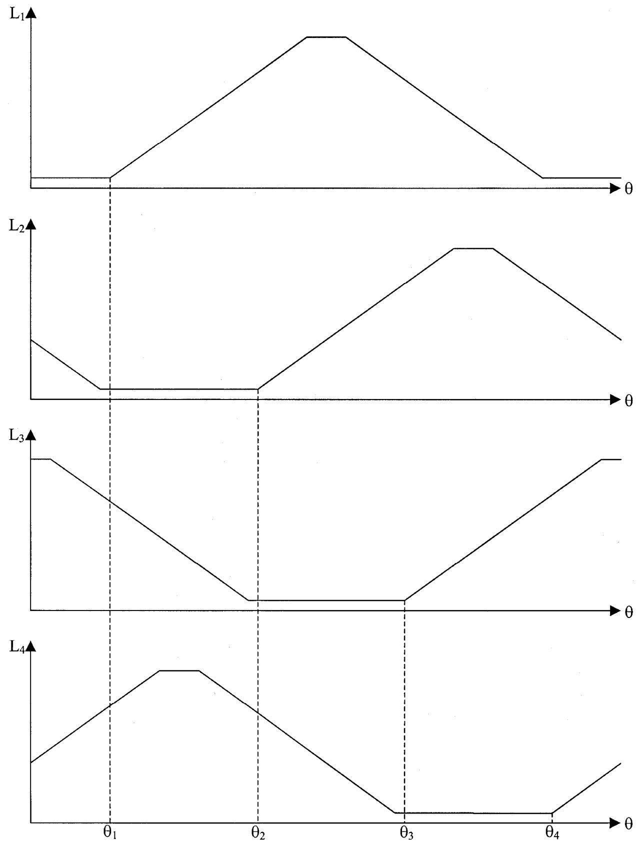


Fig. 2a — Ideal inductance profile of 4-phase SRM

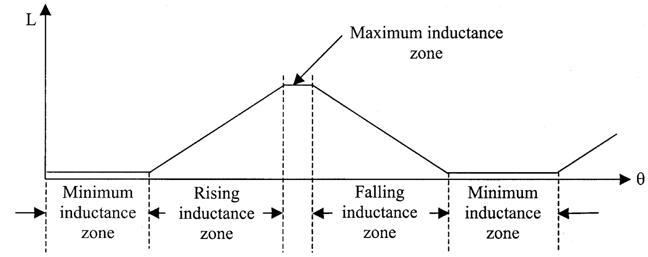


Fig. 2b — Different zones of inductance of any one phase of SRM

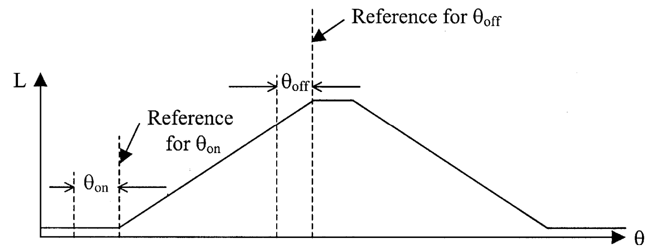


Fig. 2c — Turn-on and turn-off angles of any one phase of SRM

zone and 20° falling inductance zone. In motoring, the current is established for the positive slope region (rising inductance zone), as the developed torque is positive when $dL/d\theta$ is positive. The four phase windings should ideally become excited with reference current at instants θ_1, θ_2, θ_3 and θ_4 respectively (Fig. 2a). The respective semiconductor switches, therefore, are closed at a turn-on angle, also called advance angle, so that current in the particular phase rises to the reference current at the start of its rising inductance. Similarly, the respective switches are opened at a turn-off angle to ensure that the current in the particular phase decays to zero by the end of the positive slope region. Zero turn-on angle corresponds to the instant when a rotor pole just enters the stator pole to be excited and hence is the instant when the inductance of the excited winding starts rising. Similarly, zero turn-off angle corresponds to the instant when a leading pole of the rotor just leaves the trailing pole of the excited stator phase. This is the instant when the inductance of the excited phase has attained its maximum value and remains at this value for some time depending on the overlap of stator and rotor pole widths. Later the inductance begins to fall as the rotor pole moves away from the stator pole. Fig. 2c presents the concept of turn-on and turn-off angles for any phase winding of switched reluctance motor. The practical range of turn-on angle and turn-off angle depends on the inductance profile and therefore on the configuration and pole geometry of the particular switched reluctance motor.

Switched reluctance motor drive

The schematic of the closed loop drive system of a typical 4 phase SRM is shown in Fig. 3. It consists of outer speed loop comprising motor with rotor position sensor, speed controller and inverter. The inner current loop consists of current sensors, reference current generator, current controller and commutation logic. The working of the system is briefly discussed here so as to develop the control algorithm.

Rotor position θ is sensed by position sensor, the derivative of which gives the rotor speed ω. The reference speed ω^* is compared with the rotor speed ω. The error signal ω_e is fed to the PID speed controller. The output of the speed controller is the reference torque T^*, and is fed to the limiter. The output of the limiter is the reference current magnitude I^* for all the four phases. The signals of reference current magnitude, rotor position θ, turn-on angle θ_{on} and turn-off angle θ_{off} are fed to the commutation logic block. The commutation logic decides the phase winding to be

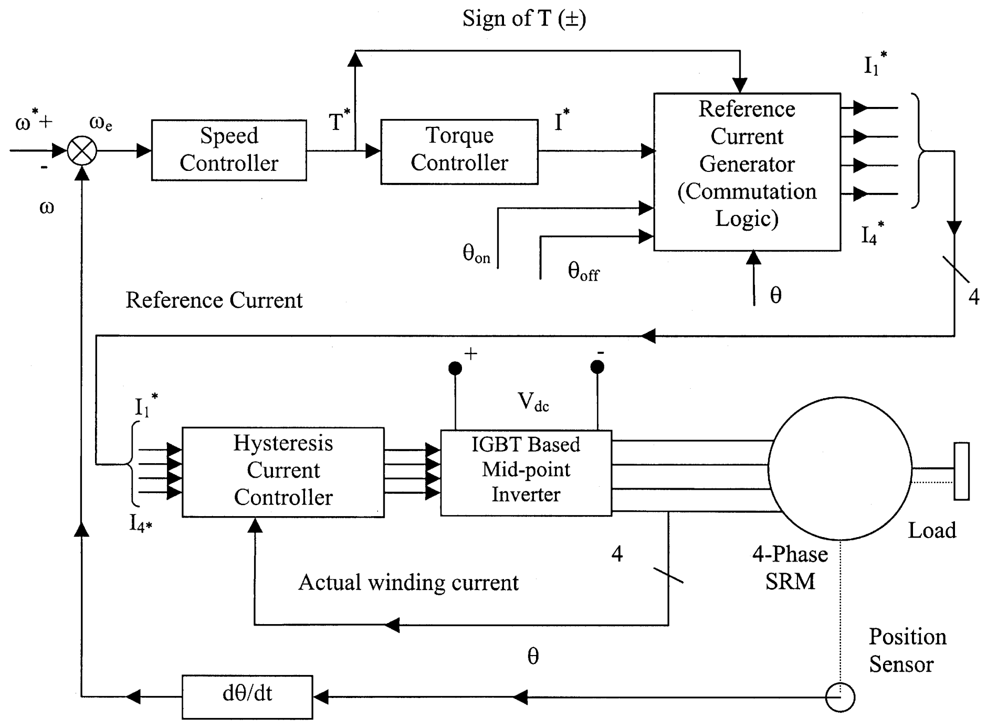


Fig. 3 — Block diagram of SRM drive system with PID speed controller

energized. The sign of reference torque signal indicates whether torque required is for motoring or braking purpose. Having identified the winding and the duration for which this winding is to be energized, the reference current magnitude I^* is latched as the reference current, say I_1^*, I_2^*, I_3^* or I_4^* for the corresponding phase windings. The winding current of each phase is sensed at the output of the inverter by the current sensor and compared with its reference counterpart in the current controller. The current controller then decides the switching (on/off) instants for the corresponding device of the inverter. In response to the sequentially controlled excitation of the windings through the inverter and controlled by the controller, the motor drives the load torque T_l at the reference speed ω^*. Any change of state in the operating condition by way of change in reference speed, load torque and inverter voltage is taken care of by appropriate control action generated by the speed controller in close interaction with current controller and commutation logic. The detailed specification of the motor used in this investigation is given in Appendix A.

Modelling

The mathematical model of SRM is a set of differential equations obtained using dynamic electric machine theory. The mathematical description of electronic controller includes the modelling of inverter, current controller, commutation logic, and reference current generator. The detailed modelling of electronic controller has been presented elsewhere[9].

Switched reluctance motor

The SRM is a nonlinear control structure and therefore it is important to develop relevant model representing the plant dynamics under various operating conditions. The model equations of the SR motor are:

$$d\psi_j/dt = -ri_j + v_j \quad \ldots (1)$$

$$d\omega/dt = (T_e - T_l)/J \quad \ldots (2)$$

$$d\theta/dt = \omega \quad \ldots (3)$$

where j=1, 2, 3, 4 represents the phase of the SRM, r is the winding resistance per phase, v_j, i_j, ψ_j are applied voltage, current, and flux-linkage respectively of phase j, T_e is electromagnetic torque developed by the motor, and T_l is the load torque. The net torque at any instant is the sum of the torque developed by all four phases, as given by

$$T_e = \sum T_j(\theta, i_j) \quad \ldots (4)$$

The model equations are numerically solved to calculate the value of flux linkage ψ, and from the experimental magnetization data[10], the value of current i is interpolated at any rotor position θ. The instantaneous torque is estimated for the known current and rotor position angle using measured static torque data[8] by quick interpolation. The experimental family of magnetization characteristics and static torque characteristics used in the analysis of SRM drive system are given in Appendix II.

PID speed controller

The rotor position is sensed by position sensor, the derivative of which gives the rotor speed. The rotor speed is compared with set reference speed and the speed error is processed in PID speed controller. The speed error at n^{th} sampling instant is given by:

$$\omega_{e(n)} = \omega^{*} - \omega$$

The output of the speed controller at n^{th} sampling instant is reference torque $T^{*}_{(n)}$, given by

$$T^{*}_{(n)} = T^{*}_{(n-1)} + K_p\{\omega_{e(n)} - \omega_{e(n-1)}\} + K_i\omega_{e(n)} + K_d\{\omega_{e(n)} - 2\omega_{e(n-1)} + \omega_{e(n-2)}\} \quad \ldots (5)$$

where K_p, K_i and K_d are proportional, integral and derivative gain constant respectively of the speed controller, and $\omega_{e(n-1)}$ and $\omega_{e(n-2)}$ are the speed error at $(n-1)^{th}$ and $(n-2)^{th}$ sampling instants respectively. The values of K_p, K_i and K_d depend on the parameters of the drive system. The complex control structure of the SRM does not necessarily lead to optimum stable performance by conventional pole placement technique. Hence, the controller gains are selected by comparing the effect of K_p, K_i and K_d on the speed response of the drive. The numerical values of PID controller gains providing the optimum performance of SRM drive are given in Appendix I. A simulation algorithm has been developed[9], which makes use of the above set of differential equations, excitation conditions, switching pattern, commutation logic and machine experimental data. Simulation of integrated mathematical model described above is carried out to compute the performance of the SRM drive system.

Switching angle

Under real-time operation as well as under simulation, the advance-angle and off-angle are calculated by the following relationship

$$\Delta\theta = LI^{*}\omega/V_{dc} \quad \ldots (6)$$

This expression is used to derive a set of fixed values of switching angles that are then examined and tested for drive performance. For advance angle calculation, the value of inductance corresponds to unaligned rotor position, which is the minimum value L_{min} or L_u. Similarly, for turn off-angle calculation, the rotor position corresponds to the aligned position and the value of inductance used in Eq. (6) corresponds to maximum value L_a or L_{max}. The speed (ω) in each case is set to the rated speed. The values of switching angles calculated by Eq. (6) are approximate since the expression is derived by neglecting the winding resistance and assuming that the magnetic circuit is linear. In practice, these angles depend upon speed and current, and the values are to be calculated at each step till steady state speed is arrived. Instead of doing all this complex signal processing, certain fixed values of switching angles that deliver optimum performance under severe operating conditions is determined after rigorous testing of drive with different pairs of switching angles.

Strategy for determination of optimum angles

The optimum single pair of switching angle is the one which gives best performance of the SRM drive on full-load at rated speed. The most logical approach is to simulate the performance when speed controller is out of the control loop and the phase-windings are excited by a constant reference current magnitude. This ensures that only the switching angles (and not the controller gains) decide the starting performance. The magnitude of reference current is kept at its maximum permissible value to allow the SRM to develop maximum possible electromagnetic torque with the given pair of turn-on and turn-off angle. The pair that brings the SRM to rated speed in the minimum time is selected, and the switching angles in their neighborhood are then further investigated.

In the next step, all the selected pairs are tested one by one to drive the SRM with PID speed controller present in speed loop, and the performance on full load is analyzed for the given performance parameters. It is ensured that fixed values of PID constants are used so that their effect is uniform for all pair of switching angles. The pair of turn-on and turn-off angle that produces minimum speed ripple and torque ripple on full-load in steady state, while ensuring a smooth starting response in terms of starting time, overshoot, undershoot and settling time is selected as optimum.

Results and Discussion

The performance of the drive system starting from standstill up to the reference speed on full-load is simulated for various fixed values of switching angles. The reference speed is set equal to the rated speed (1500 r/min) of the SRM. Speed within 1% of reference value is considered adequate for performance evaluation of the SRM drive system.

The effect of variation of switching angles is evaluated in terms of the following performance indices: (i)Time required by the motor (in accelerating from rest) to reach within 1% of rated speed (i.e. rise time); (ii) Speed overshoot over and above 101% of reference value; (iii) Speed undershoot under and below 99% of reference value; (iv) Time required to reach and stay within 1% of rated speed (i.e. Settling time); (v) Steady state speed ripple (peak to peak) on full-load; and (vi) Steady state torque ripple (peak to peak) on full-load.

The study is conducted first on full-load without speed controller in the control loop. Subsequently, study is extended with PID controller in speed loop using switching angles selected on the basis of results of the preceding study.

Starting from 0°, turn-on and turn-off angles are varied in steps of 1° in this study, but only those cases, which are necessary for performance comparison are reported for the sake of brevity.

Operation without speed controller

The speed controller is removed from the control loop while the reference current generator (commutation logic) shown in Fig. 3 is provided with a constant magnitude (23.75 A) of I^*. It is well known that besides being speed-dependent, the switching angles are also current dependent[2]. The maximum permissible value for the phase windings of the SRM is 23.75 A and it is chosen in this study because the output of any speed controller remains at its maximum permissible value till actual speed reaches near reference speed. Turn-on angle is fixed at different values while turn-off angle is varied in steps of 1°. The SRM drive performance is studied with different combinations of switching angles. Figs 4a-4e show full-load starting speed response of the SRM when the turn-on angle is fixed at 12°, 13°, 14°, 15° and 16° respectively while the turn-off angle is varied (in the range 0° to 4°) for each turn-on angle. Drive performance results with other combinations are not being presented as they are not necessary for comparison.

Fig. 4a presents the response with 12° turn-on angle and it is observed that speed fails to reach within 1% of rated value. With remaining turn-on angles, the quickest response in each case is obtained with 3° turn-off angle and this is vividly illustrated in the exploded views of Figs 4b-4e. Thus, at this stage, the optimum turn-off angle appears to be 3°. It is also observed that with best turn-off angle 3°, the minimum rise time (62.50 ms) is obtained with turn-on

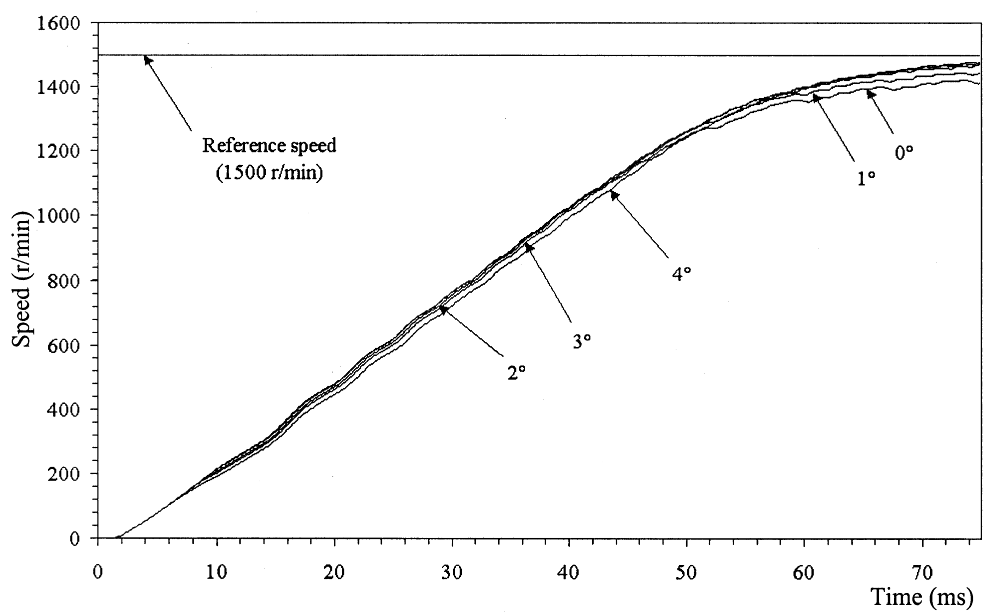


Fig. 4a — Full-load starting speed response of SRM with 12° turn-on angle and different turn-off angles, when speed controller is out of service

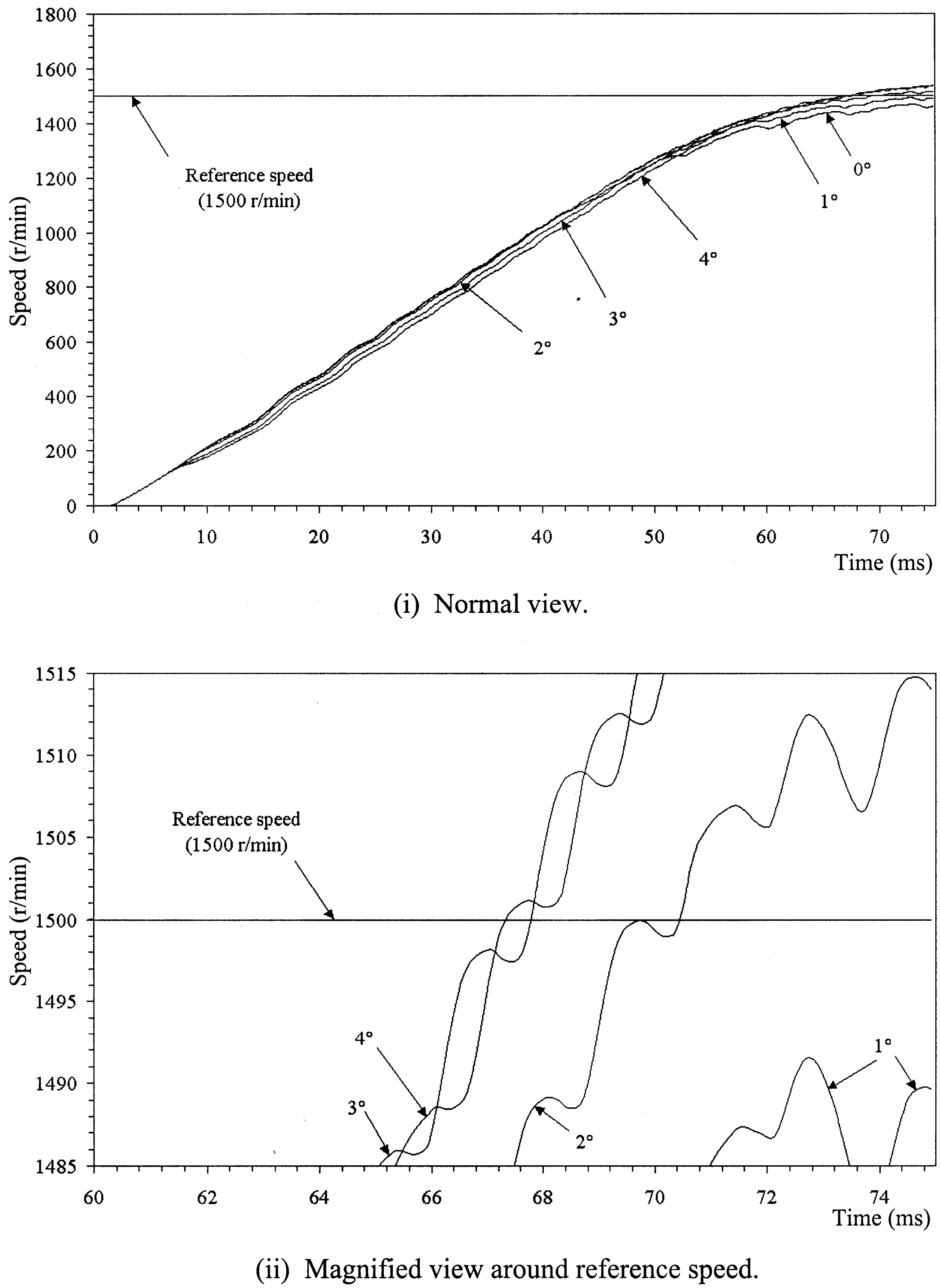
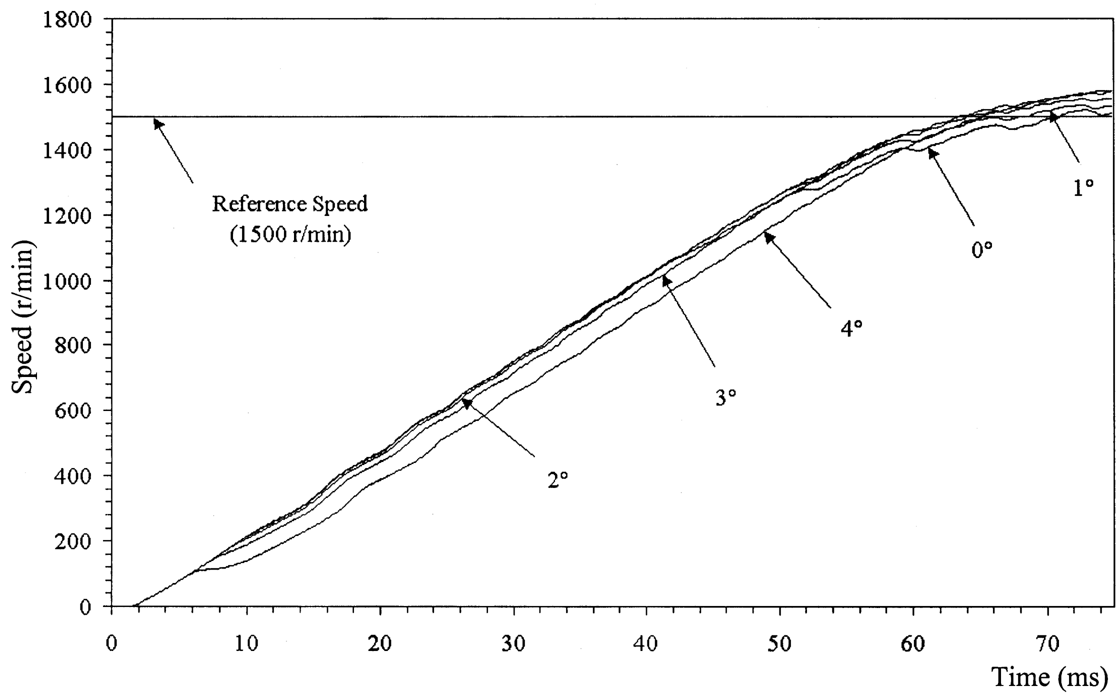
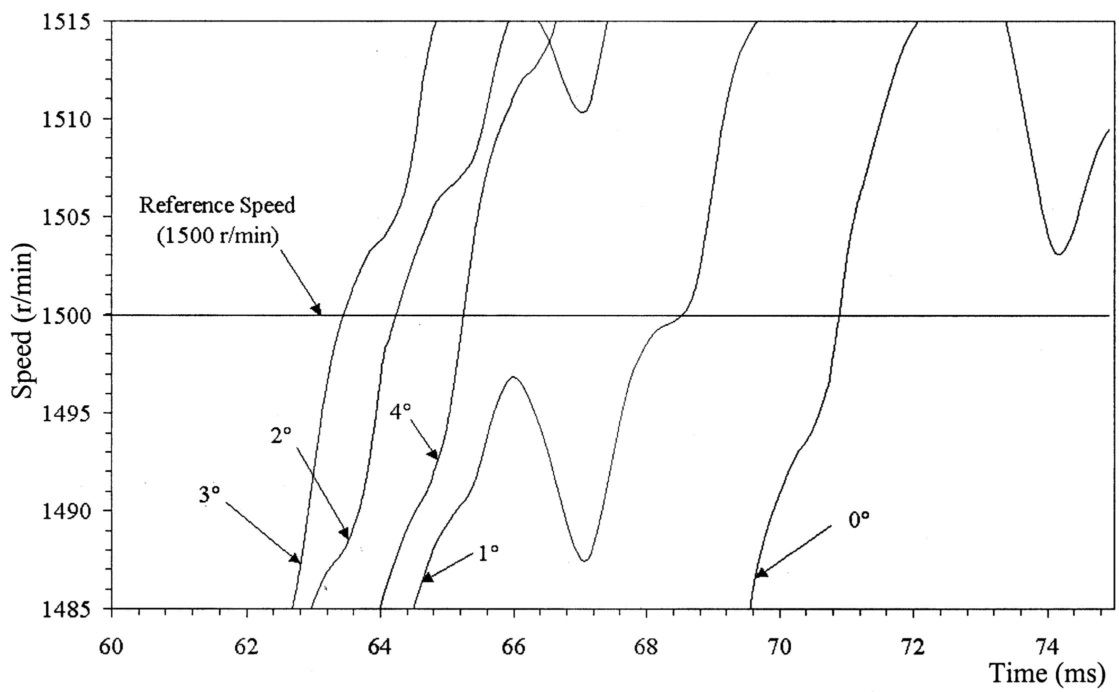


Fig. 4b — Full-load starting speed response of SRM with 13° turn-on angle and different turn-off angles, when speed controller is out of service

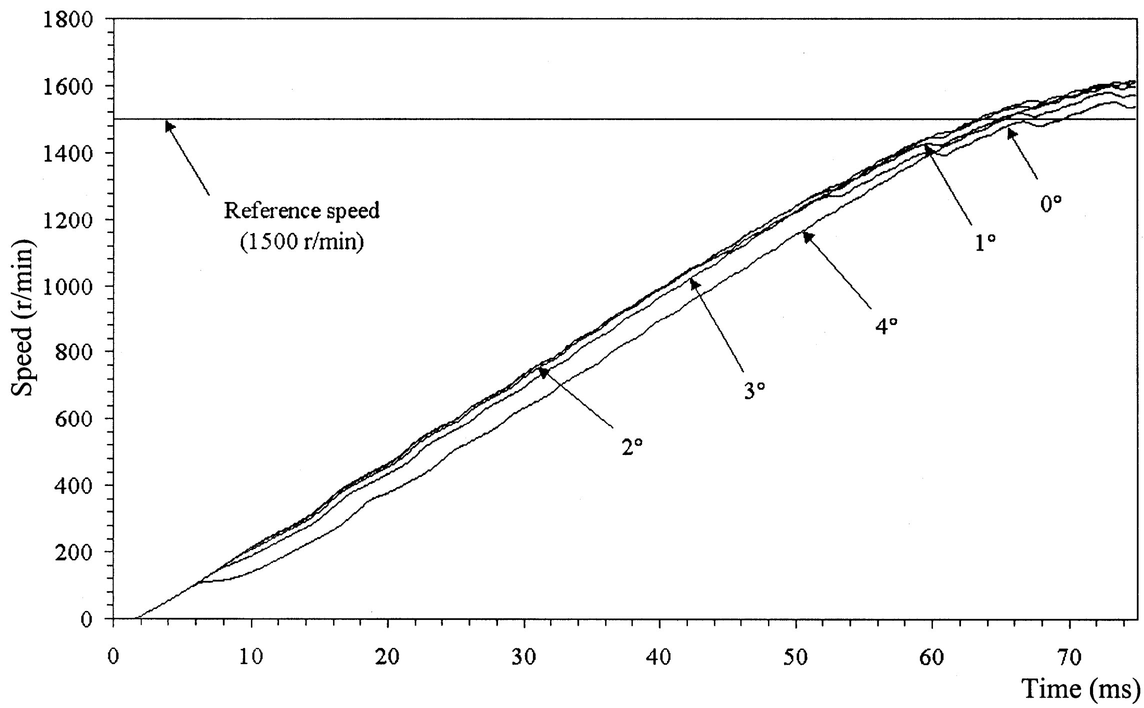


(i) Normal view.

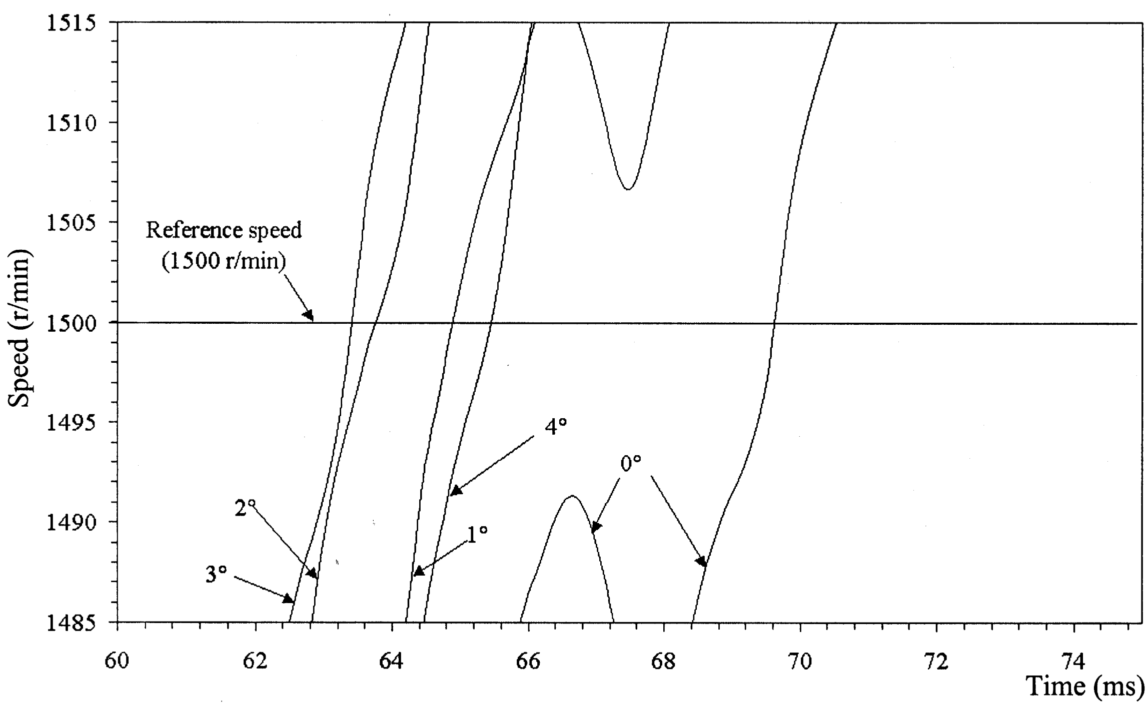


(ii) Magnified view around reference speed.

Fig. 4c — Full-load starting speed response of SRM with 14° turn-on angle and different turn-off angles, when speed controller is out of service

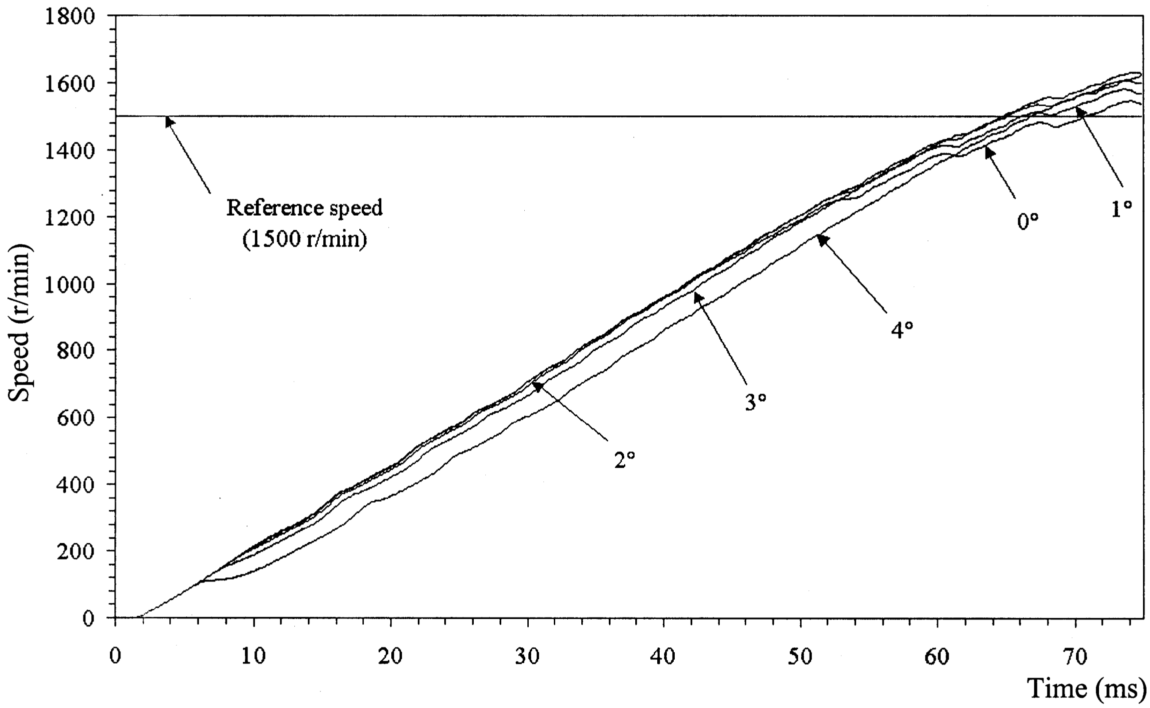


(i) Normal view.

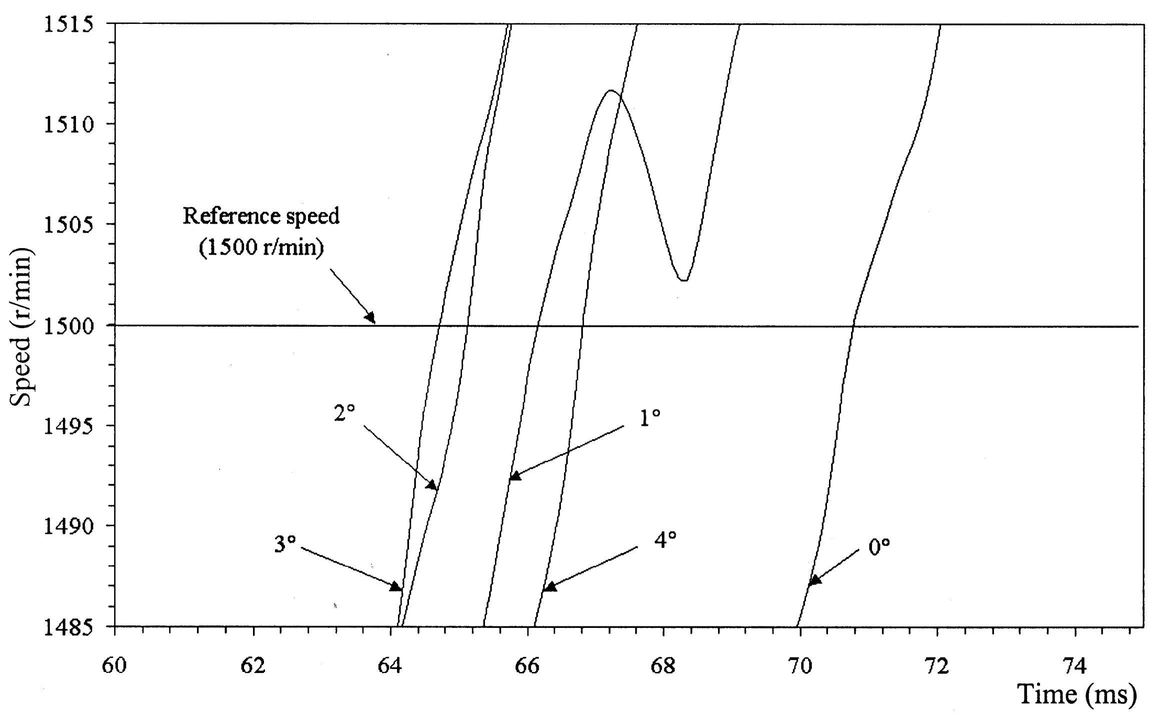


(ii) Magnified view around reference speed.

Fig. 4d — Full-load starting speed response of SRM with 15° turn-on angle and different turn-off angles, when speed controller is out of service



(i) Normal view.



(ii) Magnified view around reference speed.

Fig. 4e — Full-load starting speed response of SRM with 16° turn-on angle and different turn-off angles, when speed controller is out of service angle 15°. A summary of the rise time of SRM drive on full-load for different values of switching angles, with speed controller out of service, is shown in Table 1. It is evident from the table and speed responses that for a particular value of turn-on angle, the rise time decreases with increasing value of turn-off angle only up to a particular value of turn-off angle. In the present case, this optimum value of turn-off angle is 3°. The rise time again starts increasing once turn-off angle is increased beyond this optimum value (3°).

Operation with speed controller

The performance of SRM drive without speed controller is only indicative and not accurate. Hence, PID controller is placed in speed loop of the controller for further study. PID gains are kept constant during the course of the study so that they do not affect the comparative study involving switching angles. In order to broaden the options of testing with different combinations of switching angles, it is prudent to use immediate predecessor and immediate successor of the turn-off angle selected earlier, when the PID speed controller was kept out of service. However, in selecting the range of turn-on angle to be used for further study with speed controller in service, it is important to consider the established fact that as compared to turn-off angle, the turn-on angle plays a much significant role in the performance of switched reluctance motors. Hence, the range selected for turn-on angle must be broad enough to ensure that no significant turn-on angle is left out of the purview of the study. It also cannot be ignored that the value of turn-on angle for best performance is a variable quantity and depends on the speed and reference current at the

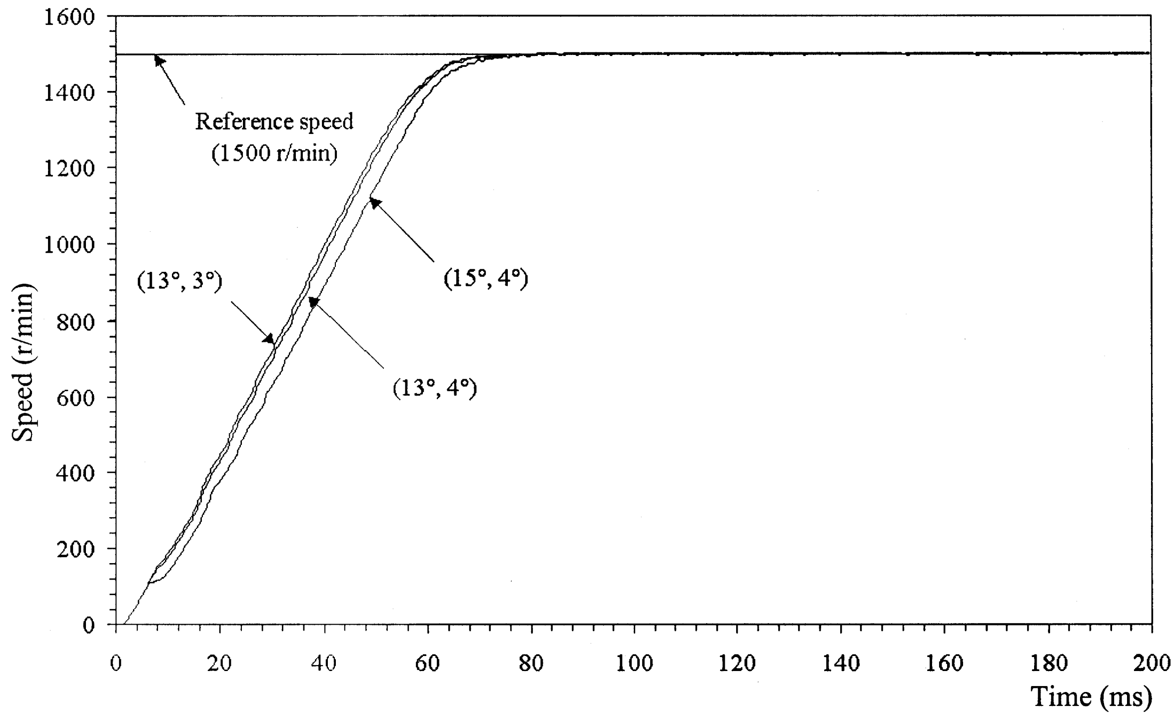
Table 1 — Rise time of SRM drive on full-load for different values of switching angles without speed controller in service

Turn-on angle (degrees)	Turn-off angle (degrees)	Rise time (ms)	Remarks
12	0	Not applicable	Speed fails to reach even within 1% of rated value.
	1	Not applicable	
	2	Not applicable	
	3	Not applicable	
	4	Not applicable	
13	0	Not applicable	13° turn-on angle provides minimum rise time with 3° turn-off angle. Speed fails to reach within 1% of rated value with 0° turn-off angle.
	1	71.00	
	2	67.49	
	3	**65.00**	
	4	65.32	
14	0	69.58	14° turn-on angle provides minimum rise time with 3° turn-off angle.
	1	64.50	
	2	62.98	
	3	**62.67**	
	4	64.00	
15	0	65.85	15° turn-on angle provides minimum rise time with 3° turn-off angle.
	1	64.20	
	2	62.82	
	3	**62.50**	
	4	64.45	
16	0	69.93	16° turn-on angle provides minimum rise time with 3° turn-off angle.
	1	65.35	
	2	64.16	
	3	**64.10**	
	4	66.10	

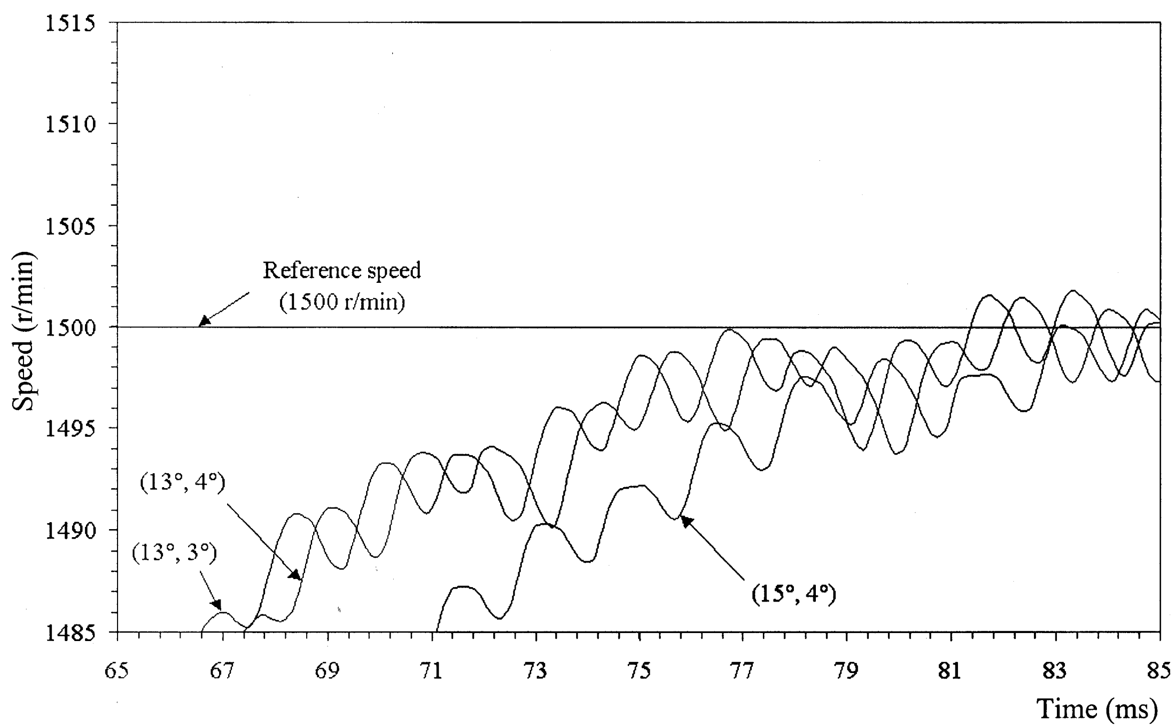
Table 2 — Performance of SRM drive on full-load for different values of switching angles with PID speed controller in service

Turn-on angle (degrees)	Turn-off angle (degrees)	Rise time (ms)	Settling time (ms)	Speed ripple (peak to peak) under steady state (r/min)	Torque ripple (peak to peak) under steady state (Nm)	Remarks
12	2	83.14	83.14	7.60 (1493.30 to 1500.90)	18.70 (17.00 to 35.70)	Turn-on angle 12° provides average quality of overall performance.
	3	79.78	79.78	8.48 (1494.7 to1503.20)	17.00 (16.80 to 33.80)	
	4	77.01	77.01	6.15 (1496.24 to 1502.39)	15.20 (18.60 to 33.80)	
13	2	67.73	67.73	5.97 (1496.43 to 1502.40)	15.55 (17.70 to 33.25)	Turn-on angle 13° with turn-off angle 3° provides best overall performance. Only speed ripple is next to best while other indices are best.
	3	**66.60**	66.60	5.23 (1497.25 to 1502.48)	**14.50** (18.50 to 33.00)	
	4	67.40	67.40	7.50 (1495.48 to 1502.98)	16.85 (17.65 to 34.50)	
14	2	67.63	67.63	5.61 (1496.52 to 1502.13)	16.20 (18.20 to 34.40)	Overall performance with turn-on angle 14° is good.
	3	68.12	68.12	5.37 (1497.15 to 1502.52)	15.00 (18.03 to 33.03)	
	4	70.37	70.37	7.13 (1495.95 to 1503.08)	16.50 (17.70 to 34.20)	
15	2	68.10	68.10	6.29 (1495.90 to 1502.19)	17.60 (17.20 to 34.80)	Turn-on angle 15° with turn-off angle 4° produces minimum torque ripple but rise time is quite high.
	3	68.70	68.70	5.43 (1497.12 to 1502.55)	15.76 (18.04 to 33.80)	
	4	71.09	71.09	**5.21** (1497.10 to 1502.31)	14.80 (18.60 to 33.40)	
16	2	69.35	69.35	7.80 (1495.65 to 1503.45)	19.80 (16.80 to 36.60)	In general, the corresponding performances with turn-on angle 16° are inferior to those with turn-on angle 15°
	3	69.90	69.90	6.96 (1495.90 to 1502.86)	19.80 (16.40 to 36.20)	
	4	72.60	72.60	5.90 (1496.50 to 1502.40)	16.20 (18.70 to 34.90)	

instant of switch-on of the phase winding. Further, with speed controller in service, the reference current becomes a variable quantity, decreasing in magnitude as speed approaches reference value. Keeping in view these factors, turn-on angles 12°, 13°, 14°, 15° and 16° together with turn-off angles 2°, 3° and 4° are used in the study with speed controller in service. Hence, full-load starting response with PID speed controller is simulated using all fifteen possible pairs of switching angles. Table 2 presents a summary of the full-load starting performance of SRM with different switching angles, when the PID speed controller is in service. Speed overshoot and speed undershoot are zero with all pairs of switching angles and hence these performance indices are not mentioned in the table. Fig. 5 shows the normal view and magnified view of starting speed response of the SRM on full-load with three different pairs of turn-on, turn-off angles (13°, 3°), (13°, 4°) and (15°, 4°). Full-load steady state torque ripple with these pairs is shown in Fig. 6. Net torque (which is the sum of the torques developed by all four windings) response of SRM with the same pairs is presented in Fig. 7 while steady state net torque ripple on full-load is presented in Fig. 8. These pairs produce best and/or second best performance in terms of the different defined indices. The best rise time (66.60 ms) and minimum torque ripple (14.5 Nm) together with next best speed ripple (5.23 r/min) are provided by the pair 13°, 3°. The pair 15°, 4° provides minimum speed ripple (5.21 r/min) and next best torque ripple (14.8 Nm), but it is the slowest of the three pairs with rise time of 71.09 ms. Second best rise time (67.4 ms) is produced by the pair 13°, 4° but it generates the highest speed ripple (7.50 r/min) and

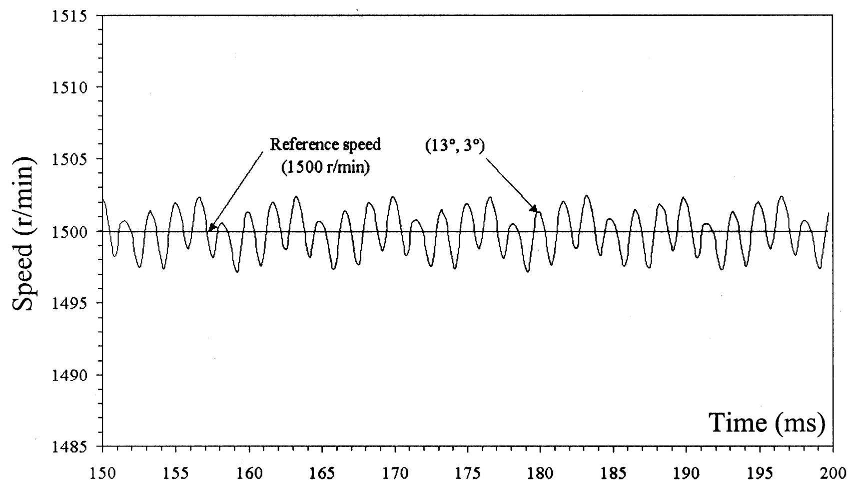


(i) Normal view.

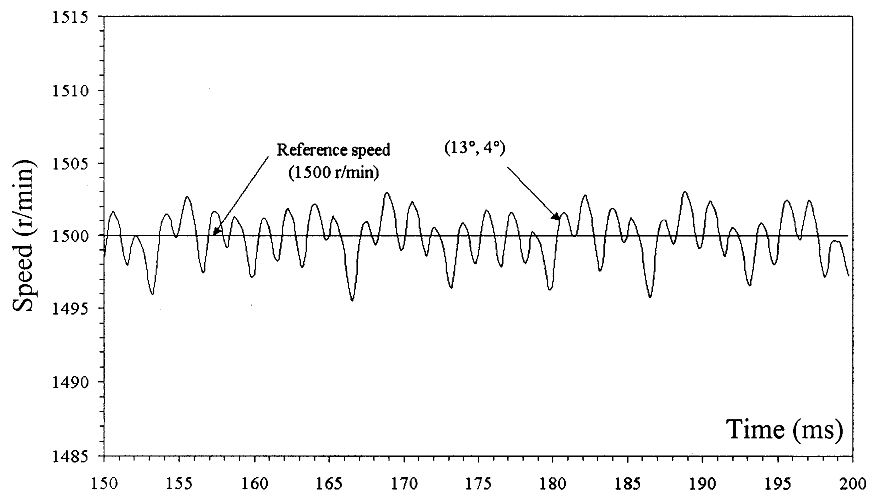


(ii) Magnified view around reference speed.

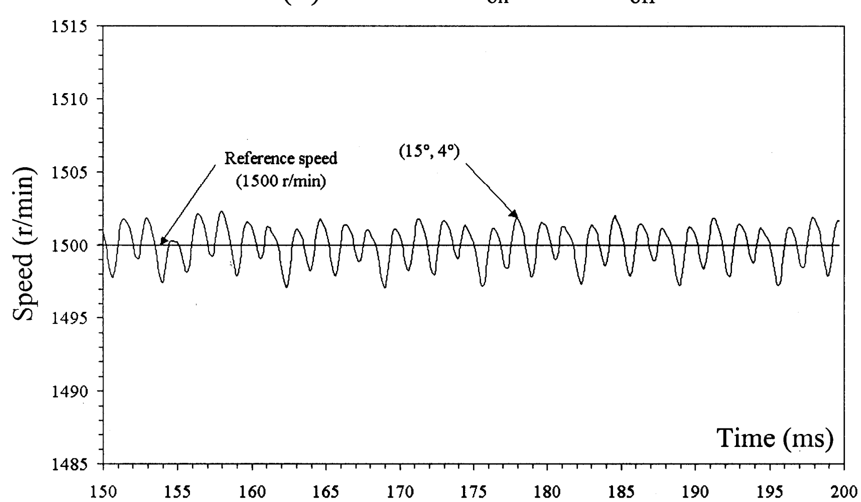
Fig. 5 — Full-load starting speed response of SRM with different pairs of switching angles, when PID speed controller is in service



(i) With 13° θ_{on} and 3° θ_{off}.

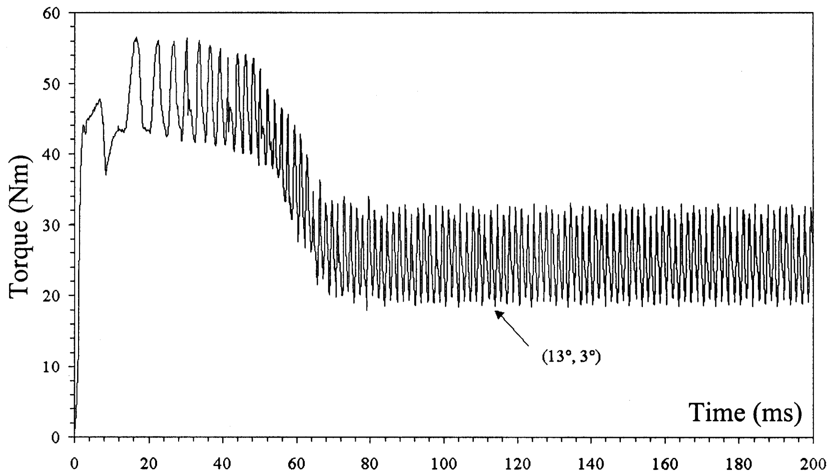


(ii) With 13° θ_{on} and 4° θ_{off}.

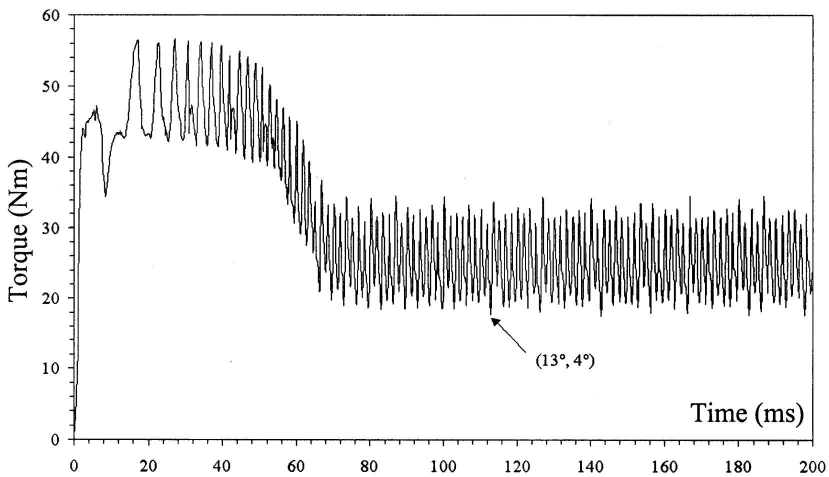


(iii) With 15° θ_{on} and 4° θ_{off}.

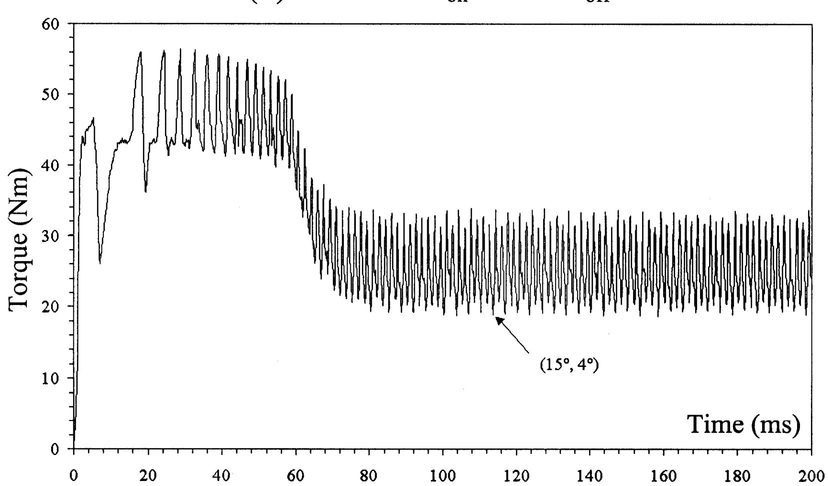
Fig. 6 — Full-load steady state speed ripple of SRM with different pairs of switching angles, when PID speed controller is in service



(i) With 13° θ_{on} and 3° θ_{off}.

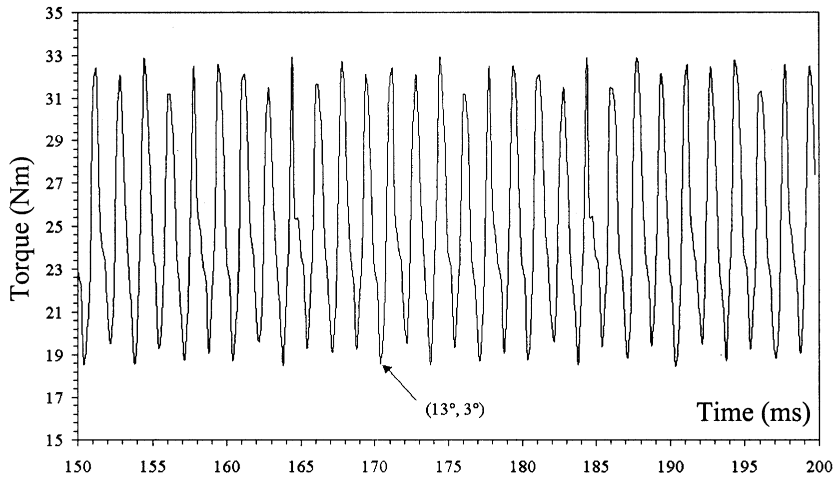


(ii) With 13° θ_{on} and 4° θ_{off}.

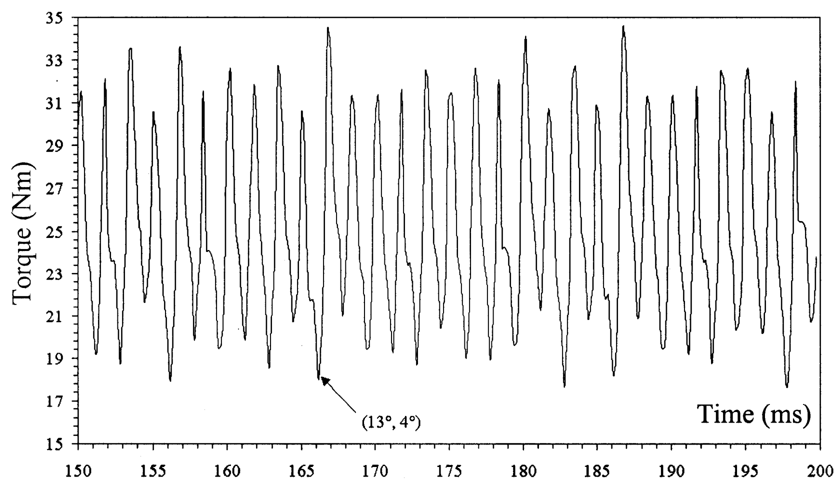


(iii) With 15° θ_{on} and 4° θ_{off}.

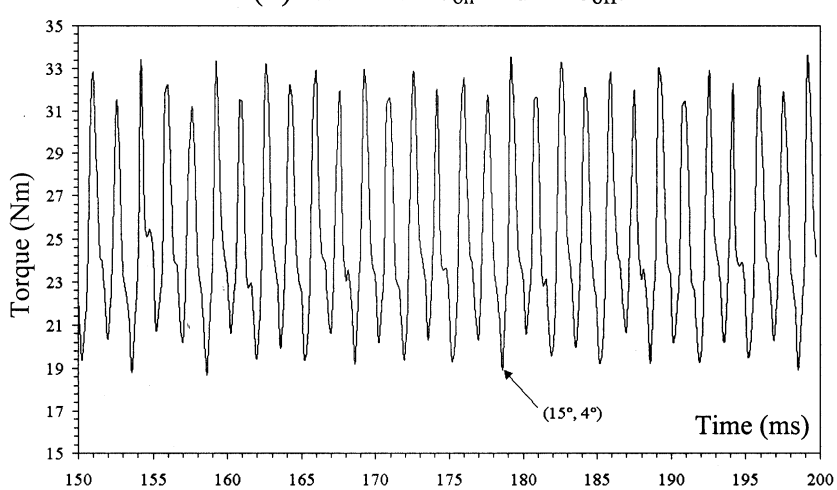
Fig. 7 — Full-load starting net torque response of SRM with different pairs of switching angles, when PID speed controller is in service



(i) With 13° θ_{on} and 3° θ_{off}.



(ii) With 13° θ_{on} and 4° θ_{off}.



(iii) With 15° θ_{on} and 4° θ_{off}.

Fig. 8 — Full-load steady state net torque ripple of SRM with different pairs of switching angles, when PID speed controller is in service

torque ripple (16.85 Nm) amongst the three pairs of switching angles.

In view of the above, the pair of 13° (turn-on angle) and 3° (turn-off angle) is selected as the optimum pair as it provides the optimum overall performance in terms of defined indices. In this case, the rise time is minimum (66.60 ms), speed overshoot and undershoot is nil, settling is immediate, steady state speed ripple on full-load is just 5.23 r/min (which is only 0.01 r/min higher than minimum speed ripple obtained), and steady state full-load torque ripple is minimum (14.5 Nm). Another very significant factor in its favour is the fact that for lower speed and/or lower load operations, a low advance angle produces

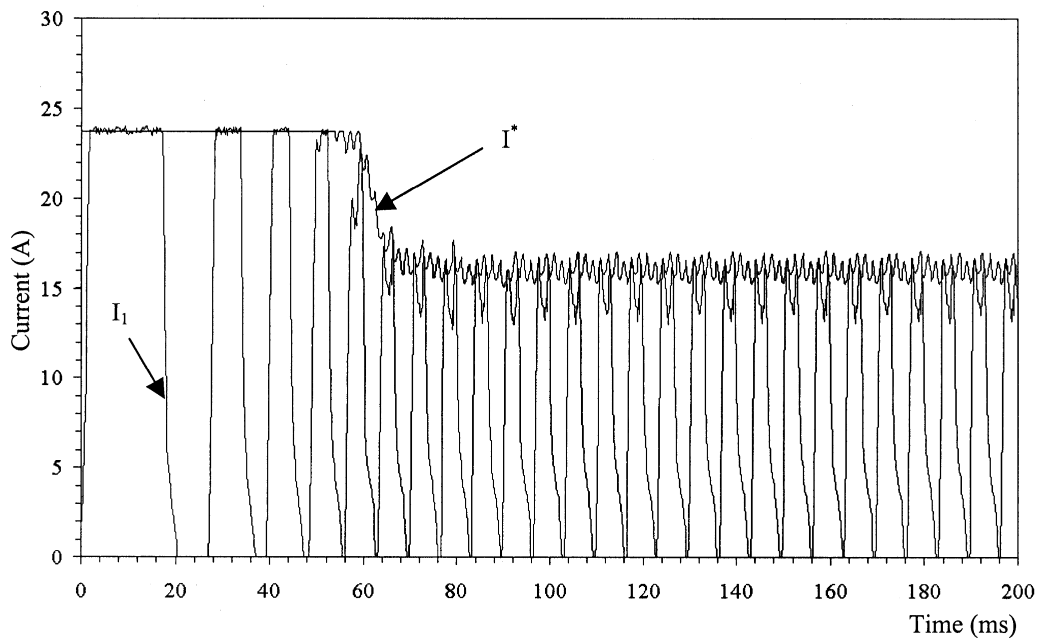


Fig. 9a — Phase-1 current response of SRM with optimum pair (13°, 3°) of switching angles during full-load starting, when PID speed controller is in service

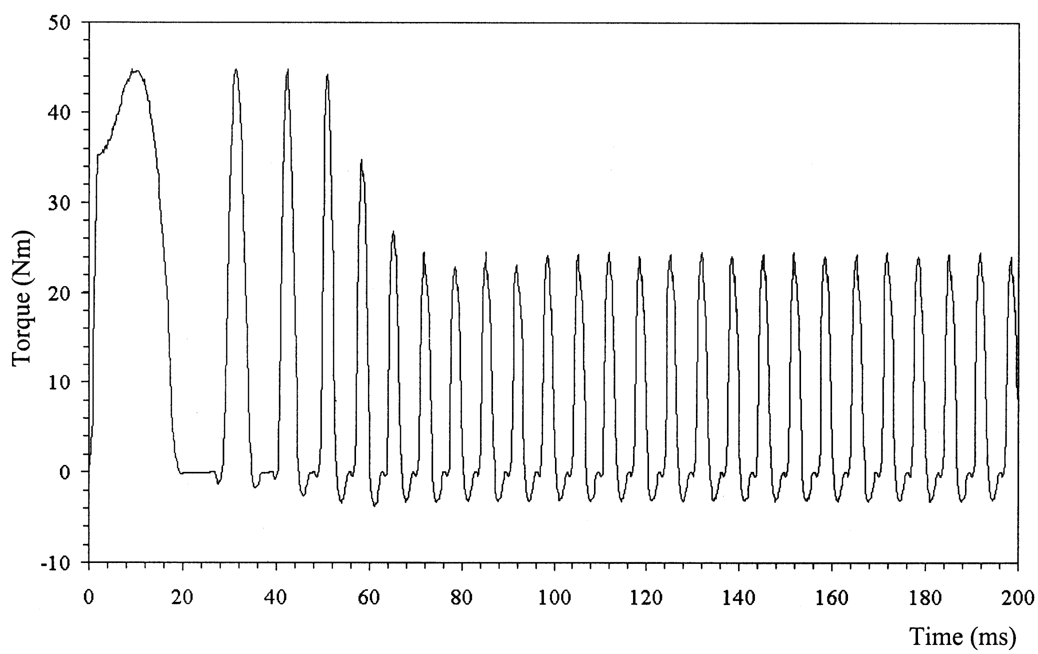


Fig. 9b — Phase-1 torque response of SRM with optimum pair (13°, 3°) of switching angles during full-load starting, when PID speed controller is in service good performance. Hence, 13° turn-on angle would surely provide better performance than 15° at partial loads and/or lower operating speeds.

Fig. 9a shows current in phase winding-1 for the optimum pair of switching angles (13°, 3°) and it is seen to faithfully follow the reference current during the switch-on period of the winding. Currents in other phase windings are of similar nature but are sequentially shifted in time. They are not being presented here due to space constraints.

Electromagnetic phase torque developed due to current in winding-1 is shown in Fig. 9b for the optimum switching angle. It is largely positive as indeed expected with optimum pair of turn-on and turn-off angles. Torques developed in other phase windings are shifted in time but have similar nature and hence are not being presented here.

Conclusions

This paper presents the study on determination of a unique fixed pair of turn-on and turn-off angle that gives optimum performance of the SRM during full-load starting. The approach adopted is logical as the speed controller is initially kept out of service and a constant reference current is furnished to the current controller. The pair that leads to minimum rise time gives an indication of the range of turn-on and turn-off angles to be used when performance evaluation is done with speed controller in service. With speed controller in service, fifteen pairs of switching angles are used and performance of SRM evaluated. It is concluded that the pair of turn-on angle 13° with turn-off angle 3° produces optimum overall performance on full-load at rated speed, in terms of the defined indices. It is very reasonably expected that this pair would produce quite satisfactory performances on partial loads and/or lower speeds as well. It is observed that the drive operates satisfactorily for the proposed fixed switching angle control and therefore this scheme should be preferred due to its simplicity in lieu of variable switching angle control requiring high speed signal processing.

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Appendix A

Motor and controller specifications

Power	4 kW
Speed	1500 r/min
No. of phases	4
DC link voltage	600 V
RMS current	9 A
Stator poles	8
Rotor poles	6
Stator resistance	0.72 Ω
Aligned inductance	150 mH
Unaligned inductance	10 mH
Moment of Inertia	0.008 kg-m^2
Proportional gain	3.4
Integral gain	0.001
Differential gain	0.01